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A cold junction compensation technique suitable for high and low ambient temperature

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Abstract : A simple, rugged, reliable, low cost compensation unit suitable for both low and high ambient temperature for a thermocouple (TC) has been developed. The specimen temperature is measured by a Chromel-Alumel type single junction TC sensor without a reference temperature bath while the ambient temperature varies from + 40°C to - 30°C For measurement of the specimen temperature in terms of voltage by a single junction TC, a voltage corresponding to the ambient temperature thermo emf is added or subtracted from the measured voltage. A Si rectifier diode IN-4148 has been employed to track the voltage corresponding to the ambient temperature

Keywords : Temperature sensors, cold junction compensation

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1. Introduction

Accurate and precise temperature measurement in widely varying environment is still a challenging problem. Various temperature sensors that are commonly availble *e.g.* resistance, diode, capacitance, vapour, gas thermometer, *etc.* have several limitations owing to the size, the speed of response, the linearity and the application range of temperature concerned. In comparison, the thermocouple (TC) has its superiority for its high speed of response, wide range of applicability, low thermal heat capacity, miniature size and low cost. The availability of standard calibration chart [1], IPTS-68 for different TC is also an added advantage. Although its sensitivity is poor (of the order of $\mu V/°C$) it is sufficient for the modern electronics to process and display this signal. The principle of the temperature measurement by TC is to measure the difference of temperature of the two junctions in terms of thermo emf E. The expression for E is

$$E = a(t_1 - t_2) + b(t_1 - t_2)^2, \tag{1}$$

where a and b are constants and t_1 and t_2 are the temperature of the two junctions of the TC.

In standard laboratory measurement, one junction is kept at the specimen temperature t_s (or t_1), while the other is kept in the ice bath at constant temperature 0°C The difficulty of maintaining an ice bath at outside or within the laboratory can be eliminated by the compensation unit which enables measurement with a single junction TC Elimination of the ice cold junction necessiates the compensation process of addition or subtraction of voltage corresponding to thermo emf of that TC at ambient temperature t_a (or t_2) to the voltage of a single junction TC. In the polar region, the ambient temperature t_a (or t_2) sometimes goes down to – 30°C or less. This paper describes one cold junction compensation technique, which covers temperature of polar region as well as normal laboratory temperature by using one commonly used Si diode.

2. Earlier work on compensation

In literature, different types of compensation techniques are found [2,3]. Normally, the laboratory ambient temperature t_a varies from 0°C to 40°C. Precise monitoring of t_s for a particular TC in terms of voltage for single junction TC, use of several solid state temperature sensors in compensation are known [4]. The output of a solid state temperature sensing semiconductor *i.e.* thermistor, sensistor of Texas Instruments and other temperature sensing devices such as AD-590, LM-5700, base emiter of 2N-2936 of Silicon Inc., *etc* are not basically linear at its first stage, but linearity is obtained by analysing and processing with the incorporated active and passive elements. The nonlinearity of two terminal temperature transducer AD-590 in the temperature range – 55°C to + 150°C, is ± 2°C [5]

3. Principle of compensation for the single junction TC

For TC (Eq. 1) the constants a and b are such that, E is almost linear over a small temperature region from – 40°C to 40°C. For the Copper-Constantan and the Chromel-Alumel TC the variation of E with temperature as obtained from the standard calibration chart [1] is shown in Figure 1. From the tabulated values of a and b for the Copper-Constantan and Chromel-Alumel TC, the second term contributes negligible. So, over a small temperature difference of t_1 °C and t_2 °C the expression of E can be approximated as

$$E = a(t_1 - t_2), \tag{2}$$

with a gain factor equal to k/a. It then becomes

$$E'' = k(t_1 - t_2). \tag{2a}$$

So when the ice bath is used the expression of E becomes $E = kt_1$ *i.e.* the thermo emf E becomes directly proportional to the specimen temperature t_1. Thus, the voltage E (= kt_2)

is to be added to the measured thermo emf when the ice bath is not used. It is therefore, essential to devise a system in order to obtain a linear voltage variation of t_a (or t_2) from +40°C to −30°C.

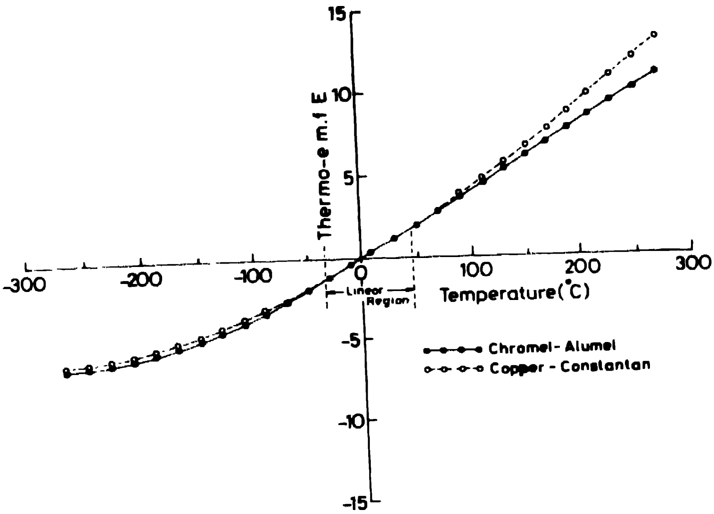

Figure 1. Variation of thermo emf with temperature for Copper-Constantan and Chromel-Alumel TC

The principle of operation of the compensation unit and temperature scale shifter from the Absolute to Centigrade scale and display of t_x in the Centigrade Scale are presented in Figure 2. The compensating diode sensor in Figure 2 generates a voltage $E = mt_2$, where t_2 is the ambient temperature, which is fed to the scale shifter. This changes the temperature

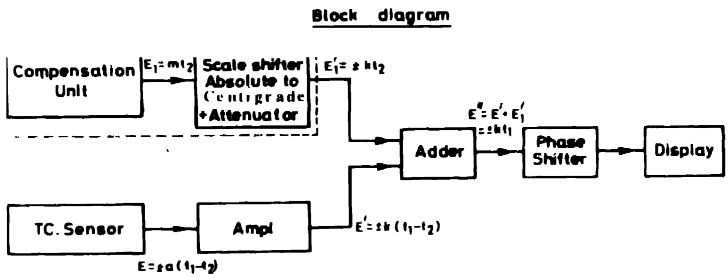

Figure 2. Block diagram of the compensation unit

from the Absolute to Centigrade scale and then attenuated to a value equal to kt_2 which is fed to the adder while the voltage from the TC sensor [$E'' = k(t_1 - t_2)$, where t_1 is the specimen temperature], reaches the adder *via* the amplifier. The output voltage from the adder $E = E'' + E' = kt_1$ being directly proportional to the specimen temperature, goes to display through the phase shifter.

4. Diode temperature sensor in compensation

Semiconductor junction has been used in ordinary temperature thermometry within limited range for more than 20 years [6]. Diodes made of Si, Ge and GaAs are being used as accurate cryogenic thermometers (2 to 400 K). They maintain good reproducibility and excellent stability of about 10 mK. However, these special purpose diode sensors for cryogenic use are expensive. These expensive diode sensors are not necessary for our present purpose. Instead of these expensive diodes, voltage-temperature relation was investigated experimentally of some commonly available Si rectifying diodes.

The voltage drop V_f across a forward biased *p-n* junction diode operating at a constant current is expressed as

$$\begin{aligned} V_f &= vkt/q \ln (I_f/I_o + 1) \\ &= vkt/q \ln (I_f/I_o), \end{aligned} \tag{3}$$

where I_f = forward biased diode current,

I_o = reverse saturation current,

T = temperature in absolute scale,

K = Boltzman constant,

q = electronic charge,

v = a consatnt = 1 or 2 depending on whether the carrier injection level is low or high.

Work on these diodes as temperature sensors operating at low level constant current source has been reported [7–9]. The variation of the diode voltage with temperature is linear with a sensitivity of 2–3 mV/°C. The empirical relation as obtained by Cohen *et al* [10] is given by

$$R = T\ (b + c \ln T), \tag{4}$$

where b and c are constants, R is the resistance of the diode at temperature T.

From eq. (4) it is apparent that for the temperature range of our interest, the diode resistance R is approximately linear with temperature for a low injection current. When a diode is connected to a constant voltage with a series resistance, the variation of voltage drop (V_r) across the sensing resistance R_s with change of temperature from + 50°C to −50°C are shown in Figure 3 with bias voltage 1, 2, 3, 4, 5 volts. The selected values of R_s are 100 Ω, 1 K, 10 K and 100 K. Voltage V_r was measured by a $6^1/_2$ digit Keithly Multimeter. Careful scrutiny of the V_r–T characteristic shows (Figure 3) that V_r increases linearly with increase of temperature in support of eq. (4) with a sensitivity of the order 1.45 mV/°C.

In the circuit, it is to be noted that the sensing diode together with all the circuits components will be subjected to a change of temperature from − 30°C to + 40°C. So, instead of a constant voltage source with negligible variation of output voltage with temperature if a constant current source is to be used, its design should be different from that of the design for operation at room temperature. By using a FET it is possible in principle, but rather difficult to construct a temperature-independent current source for such a low value of the current. The major point to emphasize is to have either a temperature-independent constant current source or a temperature-independent constant voltage source.

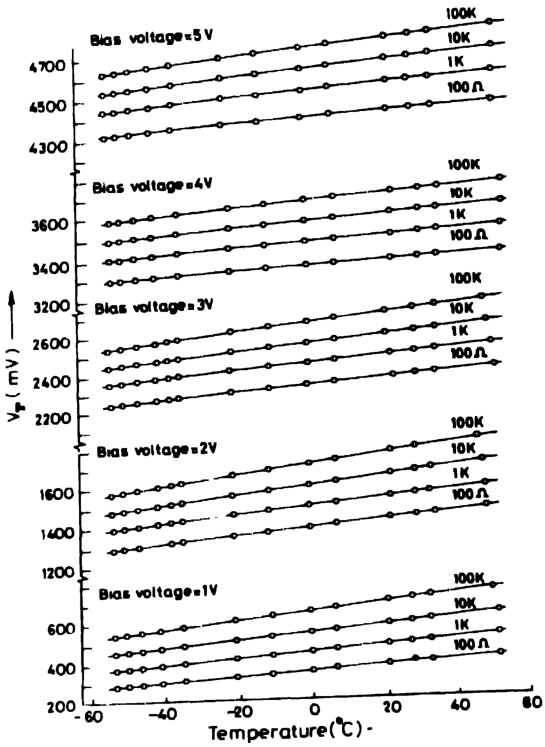

Figure 3. Variation of voltage across the sensing resistance with temperature

Since voltage reference IC LM 723 has very little variation of output voltage (0.002%/°C) with temperature [11], we have used it for the present purpose. Further, the somewhat lower sensitivity (≈ mV/°C) of the device (for further comments on this point see the section on discussion) is not a problem as such, in the present case, as it is still very high compared to that of TC (≈ µV/°C). In fact, we had to attenuate the sensitivity of the diode to match that of the TC for proper compensation.

5. Circuit description

The circuit diagram is shown in Figure 4. To construct a precise voltage reference we have used IC, LM 723. The IC voltage regulator LM 723 has a linear fall of voltage with temperature of about 0.002%/°C [11]. The reference voltage is set at a value of 1 volt and the temperature sensor diode IN 4148 has been forward-biased with a series resistance of 1 K with a combination of carbon and metal film resistance, 780 Ω and 220 Ω respectively with this reference voltage. The voltage V_r across the 1 K resistance is connected to the non-inverting input of unity gain amplifier LM 324 (I) and the output is properly attenuated with 2 K trimpot. As the TC output is scaled in Centigrade scale, an op-amp LF 351 has been used as scale shifter to this temperature scale from Absolute to Centigrade scale and the output of LM 324 (I) is fed at the non-inverting input of this FET amplifier (LM 351) The output of this op-amp is connected to the inverting input of the adder LF 351.

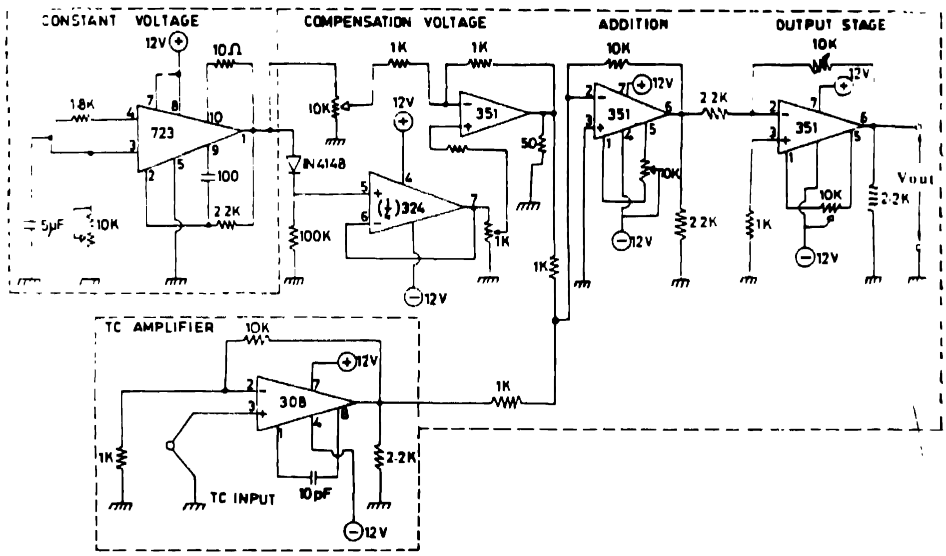

Figure 4. Circuit diagram of the compensation unit

The thermo-emf from TC is amplified by a factor of 10 with very precise FET input pre-amplifier LM 308. The output voltage is fed at the inverting input of the adder op-amp (LF 351) operating as compensation unit. The output of this adder obviously gives polarity reversal at its output *i.e.* the positive temperature is indicated by negative output signal and *vice versa* This polarity altered finally with an inverting unity gain op-amp IC LF 351 The voltage output is finally obtained from pin 6 of this op-amp LF 351 Offset voltage of all ICs (LF 351) are adjusted to zero with 10 K trimpot.

6. Testing procedure

The circuit is tested critically when the ambient temperature is varied from -30°C to +40°C, having the specimen temperature both above and below zero degree Centigrade The performance of this unit was verified by taking a two junction TC. Eliminating the compensation unit, one junction was placed in ice bath *i.e.* at 0°C and the other junction was placed at different specimen temperatures. The temperature of the specimen was varied by a temperature controlled cryostat. A curve is drawn in Figure 5 showing the variation of the specimen temperature *vs* output reading. Next we take a single junction TC and the compensation unit was incorporated. Placing the TC junction at temperatures above and below 0°C as before, the ambient temperature including the total circuit was varied by a controlled temperature bath. A curve of temperature *vs* output reading, is drawn in Figure 5. From these curves, it is observed that the two curves almost coincide *i.e.* have the same variation of temperature.

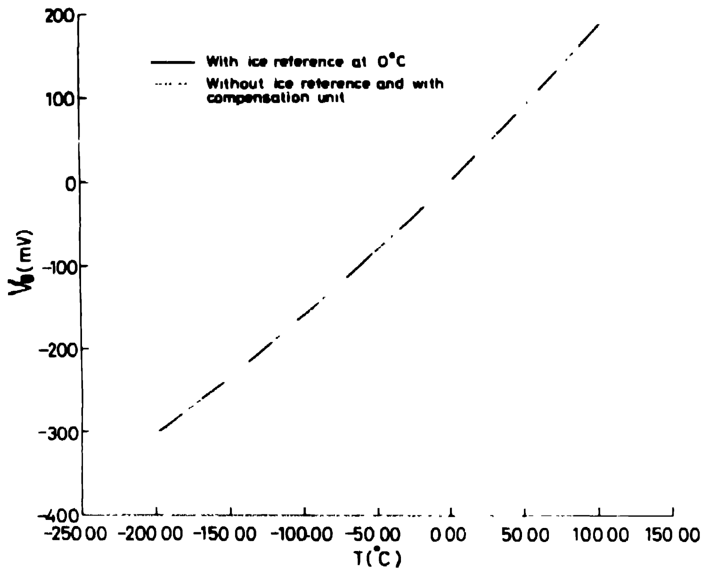

Figure 5. Variation of thermo emf *versus* temperature with ice reference and without ice reference (incorporating the compensation unit)

7. Accuracy, sensitivity and performance of the unit

The actual deviation in output (Figure 5) from the two measurements is about 0 6% The reliability, reproducibility and the performance of the unit are quite good. In the compensation process, the effect of variation of the ambient temperature from + 40°C to 30°C has been considered For further experiment, the sensitivity, linearity and the speed of response of the two temperature devices have to be perfected. The diode has a larger sensitivity ($\approx$ 1.45 mV/°C) than the TC, whereas the TC is a very fast device compared to the diode As the response speed of TC is higher, the phase lag effect can distort the operation and the output reading when the ambient temperature fluctuates rapidly In a preliminary experiment, we have found that the response speed of the diode may be enhanced to some extent if the covered glass capsule is etched out by HF acid.

8. Discussion

The unit developed has the advantage that it does not require any external switch or mechanical connection when the ambient temperature changes from above 0°C to below it Although the diode has been extensively used as temperature sensor, not much work has been done on the use of diode current variation with constant bias voltage when temperature changes as a compensation unit. The operation of the diode at constant voltage which makes the circuit design much simpler instead of the constant current source, reduces the sensitivity from 2.4 to 1.45 mV/°C. Though the reason for this drop in sensitivity is not clear, this sensitivity is still much higher compared to that of TC sensors and is sufficient for the present work. To carry out the experiment, a reference constant low temperature bath is required for verifying the performance of the circuit. The TC junction was placed in a cryostat fitted with a heater coil and the temperature controller. By using the liquid nitrogen in the cryostat, the characterisation of the diode from – 50°C to + 50°C is possible. This simple device is quite rugged and stable and may be used for measurement outside the laboratory. However, the necessity to modify the same for measuring the fluctuating temperatures often important for recording atmospheric temperature variation during storm, has been mentioned. Further work has been initiated to study the speed of response of TC and diode and how to improve the mismatch with different methods of encapsulation. It is straight forward to use some special purpose components which can achieve performance better than the present case but only at a higher cost. These may however, be necessary for circuits that we intend to design in future for high fluctuating ambient temperatures.

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